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TEMPERATURE MEASUREMENTS IN THE 30- TO 40-KILOMETER REGION

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ABSTRACT

When comparing rocketsonde and balloonsonde (radiosonde) temperature data, one notes systematic differences at levels of 25 km and above that increase with height. During the past 10 yr, systematic errors in the rocketsonde have been largely eliminated (at least for the region from 20 to 45 km), but little attention has been paid to the balloonsonde sensor. A study of temperature data for June 1967 suggests about half the difference is due to infrared cooling of the balloonsonde thermistor and much of the remaining difference may be due to the thermistor riding up through the wake of a balloon cooled by radiative and adiabatic processes. These errors make balloonsonde temperature data above 30 km unsuitable for many types of study.

During the past dozen years, the advent of the rocketsonde and the high-altitude radiosonde has opened up new areas of exploration at levels of 30 km and above. Meteorologists of many specialties have been examining these new data to determine dominant patterns of wind and temperature, typical behavior, tidal motions, estimates of momentum and energy budgets, and factors affecting ozone photochemistry. As might be expected, the quality and quantity of observation have improved considerably over the years; however, at present we do find significant systematic differences between temperatures as measured by radiosondes (hereafter we shall refer to these as "balloonsondes") and as measured by rocketsondes, at levels from 30 to 40 km. An inspection of June 1967 data, for example, revealed differences of about 1°K at 25 km, 4° to 10°K at 35 km, and 10° to 18°K at 40 km, with the balloonsonde temperature measurements being lower.

The measurement of temperatures aloft using a rocket is a rather difficult task; and not surprisingly, many early measurements suffered errors from many technical difficulties. In this system, a rocket is fired; it rises to 50 km or above; a package is ejected; a parachute opens allowing the package to descend at speeds of 50–100 m s^{-1} at 50 km, slowing to 15–20 m s^{-1} by 30 km, while the package telemeters data to a ground station and is tracked by precision radar. Synoptic meteorologists questioned much of the early temperature data; and the engineers responded with better sensors, better mounting, and standard data reduction techniques. Thus, much of the day-to-day fluctuation noted in midsummer observations of earlier years is no longer observed; and while there is concern over apparently excessive day-night differences measured near 50 km (Lindzen 1967), there are no longer any technical reasons to expect large systematic errors in the 30- to 40-km region.

On the other hand, synoptic meteorologists working with balloonsonde data from 16 to 30 km have long been familiar with instrumental difficulties that lead to systematic difference between measuring systems of different countries as well as fictitious day-night differences with each system. In general, the more advanced systems measured lower temperatures and smaller day-night difference than the older systems. At these altitudes, the air is very "thin" and consequently is relatively inefficient in removing heat from a sensor that has been affected by spurious energy from electronic equipment or the sun. Thus, meteorologists have grown up with the situation that, if the sondes are in error, they are probably reading too high.

For illustrating the systematic temperature differences, figure 1 shows the 5-mb monthly-mean temperature for June 1967 as a function of latitude. The strong, relatively undisturbed easterly winds at these levels imply very little longitudinal temperature gradient, particularly when averaged over a month. However, when examining the balloonsonde data, we see a wild scattering of points that must be smoothed to reveal the true meridional gradients. In marked contrast, the rocketsonde data show a smooth systematic latitudinal variation that inspires confidence. Looking further at the balloonsonde data, one notes that the temperatures from hypsometer-equipped sondes (solid circles) tend to be higher than those based on baroswitches (crosses), suggesting a systematic error in the baroswitch such that the sondes were actually near the 6-mb level when the baroswitch indicated 5 mb, thus giving a temperature 2° to 3°K lower than a hypsometer-sonde would have indicated. Within the hypsometer-sonde data, there was a marked dependence on solar elevation angle such that a given

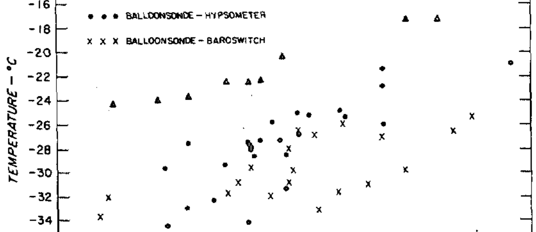

FIGURE 1.—Monthly-mean temperatures for June 1967 at 5 mb from balloonsondes and rocketsondes.

latitude nighttime temperature would read about 4°K lower than daytime temperature when solar elevation angle was above 40° (these values are consistent with values found by Finger and McInturff 1968).

A study by Ney et al. (1961) foretold difficulties that would result from using the USWB-AF thermistor (ML419/AMT-4) at levels of 30 km and above. While the engineers had coated the thermistor rods with a material that is highly reflecting in the visible spectrum, to reduce unwanted solar heating, the material is an effective emitter in the infrared (IR) and radiates excessively to space, producing systematically low temperature readings. When daytime hypsometer-sonde temperatures were compared to those from rocketsondes (nearly all daytime), the former were about 5° to 6°K lower at 5 mb (in fig. 1 the difference is 3° to 11°K, but largest differentials were with nighttime soundings). However, Ney et al. indicate a systematic error for the daytime balloonsonde of only 2.7°K. Further, Ney et al. (1961) indicate a false day-night difference of about 0.8°K due to solar absorption by the sensor; and even allowing a real diurnal up to 2°K (Finger and McInturff 1968 and Beyers et al. 1966), we cannot explain the previously noted 4°K day-night difference with hypsometer-equipped balloonsondes. Thus, we might suspect some other factors are responsible for the discrepancy between balloonsonde and rocketsonde temperatures. A second important result of the study by Ney et al. (1961) was that the temperatures of both the balloon fabric and balloon gas were much lower than those of the ambient air during ascent at night, with large "constant-level" balloons. Even while floating at constant level during the night, the gas remained colder (about 18°K lower at 35 km) but warmed up, thus having near-ambient temperatures during the day. Two effects were contributing to this difference: (1) the gas inside the balloons cools by adiabatic expansion, lowering about 10°K km^{-1} (for hydrogen, more for helium) in the stratosphere where the ambient temperature increases at about 2°K km^{-1}, and (2) the balloon fabric is also a good infrared emitter and tries to maintain a temperature close to the black body temperature at night at these levels, which may be 20°K lower than ambient air. While the data extracted by Ney et al. (1961) was based on a mylar [1] balloon material, we can reasonably expect neoprene to have similar IR characteristics. With the balloon itself considerably colder than the environment, there will be a cooling of the airstream contacting the balloon and the production of a cool wake. In the experiments reported by Ney et al. (1961), the descent temperatures ran 2° to 4°K higher than ascent, even 300 ft below the balloon; and although part of this difference is due to the ascent taking place at night with descent during sunlit hours, the difference is much larger than the predicted solar effect, so we can suspect an important contribution from a cooled wake.

To make a better test, we would like to check ascent temperatures versus descent temperatures at night and at day. Fortunately, in reducing ozonesonde data from

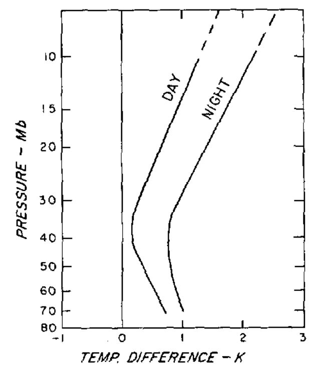

FIGURE 2.—Descent-minus-ascent temperatures at Bedford, Mass., during December 1967.

flights over Bedford, Mass., the descent data were often tabulated; and while flights are normally made during daytime, during December 1967 a number of nighttime flights were also made. When the descent temperatures were compared with ascent (fig. 2), the descent temperatures were found to be higher than ascent, more at night than during the day, and more at the highest points available (about 10 mb or 30 km) than at lower levels. However, this is not an ideal test. The sonde descends far more rapidly than it ascends (though dynamic heating is less than 0.5°K), creating difficulties interpreting the recorder chart, which is further complicated by frequent interruptions in the signal to transmit ozone information. There may also be problems due to hysteresis in the baroswitch that must be used on descent as remaining hypsometer fluid apparently spills out during tumbling at balloon burst (though this would lead to reports of higher ascent temperatures than descent). In spite of these difficulties, we do see systematic differences between ascent and descent that strongly suggest effects of a cooled wake. We would prefer to have June data instead of December and reports to 5 mb instead of just 10 mb; but wake effects as large as 2°K are indicated by this small sample.

Qualitatively, we can easily visualize a thermistor being biased as it travels upward through a balloon-cooled wake; but there are some quantitative problems. The air is in contact with the balloon (which may be 10 m in diameter at 35 km) for only a few seconds and has time to develop a boundary layer of chilled air only a couple of centimeters in depth. Even if the air temperature is lowered by 15°K and mixed with adjacent air before the sensor contacts it several seconds later, we could not have a column of air with temperatures lowered by as much as 4°K that is more than 2 m in diameter (a small diameter is consistent with wakes at high Reynolds number—about 6×10^4 in this case). If the sonde is swinging like a pendulum at the end of the 30-m line connected to the balloon, as it is normally observed to do, only rarely will it be affected by the wake. We must therefore postulate that the oscillations of the sonde are greatly damped by the time the balloon reached 20 or 25 km and the sonde becomes "captured" by the wake.

Thus far, we have noted large systematic differences between balloonsonde and roketsonde temperatures at the 5-mb level; noted that, according to Ney et al. (1961), about half this difference is likely caused by IR cooling of

[1] Mention of a commercial product does not constitute an endorsement.

the balloonsonde thermistor; and speculated (with some supporting evidence) that the remaining difference is caused by the sensor traveling up through a wake of air cooled by the balloon. The rocketsonde data present a relatively orderly variation of temperature with latitude (inspiring confidence); but we can always ask, "Is this the correct variation?" If there are systematic effects of solar radiation or IR cooling on the rocketsonde, we might expect the latitudinal temperature profile to be incorrect. As a test, we can use the thermal wind equation to solve for the temperature gradient, integrate the gradient over latitude, and compare the computed temperature profile with the observed.

Thus, we solve

$$\frac{\partial u}{\partial p}=\frac{R}{fp}\frac{\partial T}{\partial y}$$

for T and obtain

$$T=T_0+\int\frac{f}{R}\left(\frac{\partial u}{\partial(\ln p)}\right)dy$$

where u is the west wind; p, pressure; f, Coriolis parameter; R, gas constant of air; T, temperature; T_0, temperature at a reference point; and y, distance north. T and u are monthly-mean values. To evaluate this expression, we obtained u at 10 mb and 5 mb from rocketsonde and radiosonde data; T_0 was estimated as -29°C at 30°N for the 10- to 5-mb layer, using nearby rocketsonde data. The continuous line in figure 3 shows the resulting temperature profile; the triangles are values from rockesondes. The agreement is quite good; with only five to 19 observations at any one station and a standard deviation of about ±3°K, the departures are no more than might be expected by chance. In addition, the sample is not homogeneous in that stations from 15°N to 35°N made a temperature correction and others did not (nearly all observations were with the Arcasonde 1A). Clearly, the rocketsonde temperatures are giving us the correct north-south profiles; and if there are IR or solar radiation effects, they must be negligibly small or fortuitously compensating.

We should note that the latitudinal integration was based mostly on the balloonsonde wind data. Since most of the rocket observations were made near 1000 LST, we have a bias due to the relatively large vertical variations of the diurnal winds at these levels (Muench 1968). When using balloonsonde observations taken at both 0000 and 1200 GMT and at varying longitudes, the diurnal was largely "smoothed" out.

At this point, we must conclude that balloonsonde temperature data for levels above 30 km (perhaps above 25 km) should be used with great caution. These data cannot be directly used to calculate diurnal temperature variations although Finger and McInturff (1968) obtained some information through careful processing and a few assumptions. Annual temperature variations are suspect where there are large changes in solar elevation angle from season to season, particularly if one season is in darkness. While these data can be used to examine day-to-day or even week-to-week temperature changes

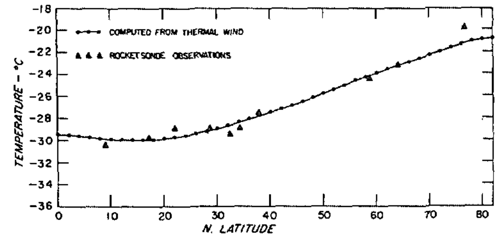

FIGURE 3.—The 10- to 5-mb rocketsonde temperatures for June 1967 as a function of latitude; the profile was computed from thermal wind relationship.

TABLE 1.—*Estimated errors and corrections for balloonsonde temperatures for June*

	Sensor		Wake		Correction	
Millibars	IR	Solar	Night	Day	Night	Day
5	−3.5	+1.1	−4.0	−2.0	+7.5	+4.4
10	−1.8	+ .8	−2.2	−1.1	+4.0	+2.1
20	− .5	+ .7	−1.3	− .6	+1.8	+ .4

at a given station, one would have to use a correction table to reduce fictitious darkness-daylight effects to study the large-scale patterns. For studies of thermodynamics and ozone photochemistry, correction factors must be applied to the data, leaving the question, "What are the corrections to be made?" As a rough estimate for June, the following systematic errors are suggested in table 1.

Undoubtedly, comprehensive correction tables will be computed and published; but the users would really like a better sensing system for the balloonsonde at those altitudes. A better thermistor coating as suggested by Ney et al. (1961) could be a start. If the wake problem is as serious as suggested here, some major engineering will be required to obtain unbiased temperatures (e.g., sensor on top of the balloon or on a long outrigger). Certainly, there are many advantages to using the balloon system for the 30- to 40-km region; but the temperature data should be accurate enough to justify the effort.

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